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# Simulation Fidelity Issues for Nuclear Survivability Validation Protocols



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This report presents a top-down discussion of broad simulation fidelity issues as they apply at each level of integration, from the highest (system of systems – SOS), through each succeeding lower level, i.e., system element (SE), system element platform (SEP), subsystem, component, and piece part/materials. Types of simulations applicable at each level are identified. Possible approaches that can improve simulation fidelity, to include a discussion of potential artificial intelligence applications, are presented.

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# SUMMARY


The advent of complex, highly interdependent systems of systems requiring survivability with high confidence will place increasing reliance on the use of simulations to validate survivability. Past testing and simulation approaches will be inadequate to fully test such systems of systems. We must, therefore, address simulation fidelity issues in a broader context than we have in the past.

Traditionally, the nuclear weapons effects community has considered simulation fidelity to be how faithfully a nuclear weapon effect simulator replicates the environment produced by a threat weapon. This definition addresses only part of the problem posed by attempting to validate the survivability of a complex, interdependent system of systems. Simulation fidelity issues not only apply to how well we can simulate the environment, but also to how well we can model the effects and the system response to those effects. This concept must be expanded to include all physical and computational tools used to test, assess, and validate system survivability.

This paper presents a top-down discussion of these broader simulation fidelity issues as they apply at each level of integration, from the highest (system of systems - SOS), through each succeeding lower level, i.e., system element (SE), system element platform (SEP), subsystem, component, and piece part/materials. Types of simulations applicable at each level are identified. Possible approaches that can improve simulation fidelity, to include a discussion of potential artificial intelligence applications, are presented.

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## SECTION 1

## INTRODUCTION

The purpose of this paper is to address the issues of simulation fidelity as they affect our ability to validate the survivability of complex systems of systems. Nuclear survivability validation relies on simulations at many levels of system integration, and hence the fidelity of these simulations is a concern at all of these levels. In this paper we use the term simulation fidelity to refer to the fidelity (accuracy, faithfulness, inclusion of the relevant features, or precision) of physical or computational simulations used in the survivability validation process. This is a broader application of the term "simulation fidelity" than is commonly used by the nuclear weapons effects community, where it usually refers to how well a physical environment simulator, such as a flash x-ray machine, can reproduce some aspect of a nuclear environment. Under our broader definition of simulation fidelity, we also include both computer code simulations and mixed (hybrid) hardware/software simulations. Furthermore, we consider not only the fidelity of the environments and effects, but also the fidelity of the system elements and element responses.

In this paper, we present a "top down" approach, starting with the highest level of integration, a "system of systems" (SOS), and working down to the lowest levels (e.g., piece parts and materials). Examples of complex, interdependent SOSs include Global Protection Against Limited Strikes (GPALS), MILSTAR, Theater Missile Defense (TMD), and the Trident Submarine fleet. The terms used for the various levels of integration in this white paper are indicated in Table 1-1.

**Table 1-1. Hierarchy of levels of integration of a system of systems.**

| Level of Integration (Highest to Lowest) | Examples |
|---|---|
| System-of-systems (SOS) | GPALS, MILSTAR, Trident, Theater Missile Defense |
| System element (SE) level | Constellations of satellites or Brilliant Pebbles |
| System element platform (SEP) level | A radar, satellite, an individual Brilliant Pebbles, a missile |
| Subsystem level | Power subsystem of a satellite, seeker of a kinetic kill vehicle, post-boost vehicle guidance system |
| Component level | Individual electronics boxes, lenses, mirrors |
| Part/material level | Baffle materials, piece parts |

In Section 2 we classify the kinds of simulations that are important in survivability validation protocols. The role of simulations at the various levels of integration, starting with the highest level and moving down to the lowest levels (the piece part and materials level), is considered in Section 3. Also in Section 3, various simulation fidelity issues are identified. Conclusions and suggestions for improving simulation fidelity in the context of an integrated perspective of the entire survivability validation issue are presented in Section 4.

# SECTION 2

# KINDS OF SIMULATIONS FOR SURVIVABILITY VALIDATION (SV) PROTOCOLS

Three kinds of simulations used in survivability protocols must be distinguished: (1) purely computer, or software simulations, (2) physical hardware test facility simulations, and (3) combination, or hybrid software/hardware simulations.

## 2.1 COMPUTER AND ANALYTIC SIMULATIONS.

In computer or analytic simulations, the SEPs (or portions of SEPs), responses, nuclear environments, and nuclear effects are all simulated with software. These simulations further break down into two distinct types, according to whether a large aggregate of element platforms is being simulated, or whether the basic physics of a nuclear effect at a much lower level is being simulated, represented, or studied.

Type (a). System analysis codes, such as engagement scenario or war game types of simulations, with hostile environments simulated. Examples of codes that are used in conjunction with the engagement codes to permit simulation of persistent environments are PEM, HiSEMM, NORSE, MICE, MELT, SCENARIO, AMEM, and RANC. In the engagement codes, prompt nuclear effects as such are not really simulated, but merely accounted for by some table look up procedure (for example, an SEP either fails or survives, depending on whether total dose is above some threshold value). Such codes may be applied to the SOS or to a portion of it to determine SE requirements (such as the National Test Bed (NTB) System Simulator of SDI in its "Level 1" role). Or, they may be applied to the entire SOS to demonstrate or to assess mission survivability of the SOS (as it is done with the NTB System Simulator in its "Level 2" role).

Type (b). Nuclear weapons effects codes, models and analytic techniques used to calculate responses and secondary environments on components or subsystems. These include first principles physics approaches as well as empirical and engineering level approaches.

The code simulations of type (a) are the systems analysis codes designed to model SOSs. These codes are used to assess questions regarding defense system architecture and force-level effectiveness. Since these codes are used primarily in trade-off studies, many simplifications are generally made to bring computer run-time down to a level where a defense systems analyst can make a large number of comparative runs in a relatively short period of time. An example of such simplifications might be the use of flyout contours to model interceptor performance rather than including a six degree-of-freedom performance model.

As we have said, nuclear effects are usually represented in a greatly simplified way in the engagement codes: they are either treated in a cursory or probabilistic fashion or ignored altogether. For determining baseline expected system effectiveness in a non-reactive environment, this approach often proves sufficient. Here, nuclear effects are often assessed by calculating vulnerability numbers (VN) for direct blast effects and using a geometric analysis to determine fireball/cloud effects. After baseline effectiveness has been calculated, the systems analyst must concern himself with potential countermeasures (CMs) that the offense might take to regain damage expectancy. Such CMs might include salvage fuzing of the warhead, intentional precursor bursts, "laddering down" reentry vehicles to attack defenses irectly, or direct attacks on space-borne sensors or communication assets. All of 1ese CMs involve some level of simulating nuclear effects on the defense system.

In simulations such as these, a major question that must be addressed in the onstruction of the models is at what degree of fidelity the various environments are 1odeled (or whether they are even included). The decision is usually based on omputer run-time considerations, available funding for simulation model levelopment, perception of what the survivability determining effects are, and xpertise at hand. Historically, all engagement codes have addressed the effects at he microscopic level. In no case have global, force-level engagement models ıttempted to include effects at the materials or individual sub-component parts evel.

Code simulations and analysis of the second type (b) play a very crucial role in urvivability assessment, especially in hardness assessment at the SEP level and elow. It is arguable that most testing serves primarily to validate, calibrate, check, or verify the analytic tools, which are used to predict responses of the system to the allowed ranges of the nuclear threat, and ultimately to assess the survivability of the system. This is because all tests, whether UGT or AGT are, to varying degrees, mperfect simulations of threat environments, and extrapolation or interpolation to threat conditions using a model incorporating the relevant physics is required. Hence, there is a sense in which the entire survivability protocol involves end-to-end computer simulation.

Traditionally, the two basic types of computer programs (engagement and effects) are exercised separately. The various nuclear effects are generally studied first, with the help of the appropriate computer and analysis tools, and the results are incorporated into the engagement codes as *look-up* tables, fitted functions, or statistical distributions. The engagement codes can then calculate approximate effects levels and either use a cumulative level or sample a random variate and compare it to a failure probability to determine the effect on the SE or SEP being assessed or simulated.

Some of the analytic tools consist of purely analytic methods (simple equations, back-of-the-envelope calculations, simple algorithms, etc.), algorithmic or analytic codes (based on more complex equations and algorithms), as well as computer simulations proper. We may consider all analytic tools to be types of simulations, even when software as such is not involved. Examples of algorithmic or analytic codes include the DNA Box IEMP code, all of the cable SGEMP driver codes, and analytical transport codes (such as BUCKL, QUICKE, ANISN, and CEPXS).

By "computer simulations proper" we mean those codes that involve conventional numerical simulation techniques, such as finite difference models, finite element models, statistical sampling such as Monte Carlo techniques, etc. The key feature is that the response being calculated is not expressible in closed mathematical form as it is in the case of algorithmic codes, but is actually simulated on a time and/or special grid of some sort. These kinds of codes tend to be based on "first principles physics." They can be one, two, or three dimensional. Hydro codes are a good example of this type of code. Other examples include the SGEMP self-consistent particle pusher type of code, the structural response codes, such as ABAQUS or SHELLSHOCK, and the Monte Carlo transport codes (such as SANDYL).

The concept of "simulation fidelity" can be applied to all of these types of code and analytic simulations. Whereas simulation fidelity in testing can be increased by building machines with new technology that permits a better representation of the environment, simulation fidelity in code and analytic simulation can be improved by advances in computer technology (increases in memory and speed, which might allow such fidelity improvements as finer special gridding, smaller time steps, more environment versus response functions, etc.) as well as by improved understanding and modeling of the relevant physics. Validation documentation and configuration management of software tools will also contribute to simulation fidelity.

## 2.2 PHYSICAL (HARDWARE) ENVIRONMENT AND EFFECTS SIMULATION.

Physical (hardware) test facilities can also be broken down into three types:

(a) Those simulating some selected component of a nuclear environment. Examples of such AGTs are flash x-ray simulators, fast burst reactors, EMP facilities, gamma-ray machines, and high explosive tests.

(b) UGTs. While these afford the opportunity for testing in a relatively high fidelity, multi-faceted, actual nuclear weapon environment, there are some fidelity limitations even here. One important point is that not all nuclear environments are present in a UGT test bed, due to test conditions and the closure mechanism (for example, debris gamma and IR are not significantly present).

(c) Those simulating a secondary environment. These include current injection tests (CITs) for EMP, SREMP, SGEMP, etc. Other examples of this type of test are magnetic flyer (for shock and impulse), LIHE, thunder pipe, gas gun, etc.

The CIT can be viewed as a kind of "scene generator" of sorts, but where burnout or upset of electronics is the effect under study (rather than redout or blackout, for example). The CIT has limitations or drawbacks which are in a sense simulation fidelity issues: one must know how to calculate the correct secondary environment (rather than relying on the environment to generate it), synergistic effects such as SGEMP/TREE are not present (unless radiation tests are underway simultaneously), and simultaneous injection or drive of all connector pins is not usually possible.

## 2.3 COMBINATION HARDWARE/SOFTWARE SIMULATIONS.

In this type simulation, some of the system elements can actually be present (often in modified form, which raises another fidelity issue). An example is where an actual $C^2$ center is present along with an actual radar with a scene generator to provide simulated targets and perhaps simulated nuclear blackout environments. The links to ground-based interceptors might actually be present, but software might be used to simulate interceptor launch, intercept, and response in the presence of nuclear environments. In some of these simulations, there may be provision for the man-in-the-loop, whether or not any actual hardware is present. The concept of a hybrid SOS simulation is depicted in Figure 2-1. Such hybrid simulations, involving man and hardware-in-the-loop (to the extent possible) might be valuable for ultimate survivability validation. Such a large scale simulator was being developed for the SAFEGUARD ABM by Bell Labs in the 1970s, and was known as the system exerciser.

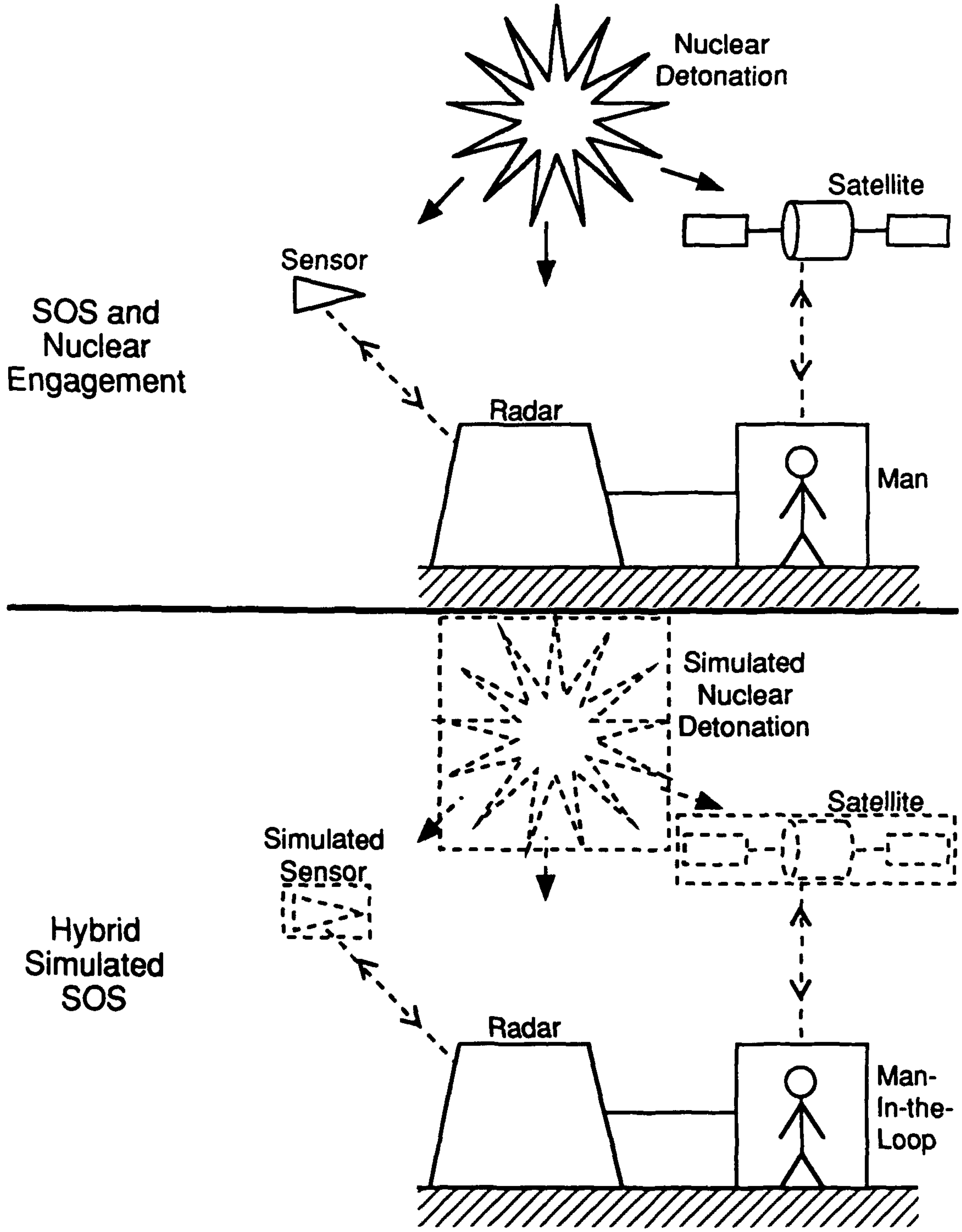


**Figure 2-1. Example of a hybrid simulation at the SOS level.**

## SECTION 3

## SIMULATIONS AT THE VARIOUS LEVELS OF INTEGRATION

### 3.1 HIGHEST LEVEL OF INTEGRATION (SOS).

For a complex SOS with multiple interdependent elements and communication links, there is no way, short of a nuclear war, to test the entire SOS in a real nuclear environment. In simulations at this highest level of integration, the entire SOS itself, it is necessary to use software to simulate the nuclear weapons environments and their effects on the SOS. In these SOS simulations, varying degrees of actual hardware may be present. In end-to-end software simulations, the system elements, enemy forces (or enemy elements), and nuclear environments and effects are all simulated on the computer. Certainly this kind of tool is necessary to support system development and determination of element requirements (partly because hardware will not even exist during earlier periods of development, but also because of the convenience, flexibility, and lower cost of a purely software tool).

At the SOS level, "the threat" must be considered to consist of a complex set of scenarios involving a range of hostile system capabilities, and each SEP will generally be subjected to a different nuclear environments in a given engagement scenario (some SEPs seeing no direct nuclear environment at all). In the present context of nuclear survivability validation, there are several fidelity issues. For example, how faithfully are the nuclear environments, system responses, and nuclear effects modeled?

There are basically two categories of simulation information required, corresponding to the friendly forces (the SOS) and the hostile forces. Not all of this information describes physical systems; it includes such virtual items as communication links and rules of battle/engagement for both the offense and defense. To accurately model the SOS to assess its survivability, one must be able to define or make assumptions about the following:

- Defense (Friendly forces)
  - Defense release decision making process
  - Communication links (connectivity and bandwidth)
  - Communication magnitude (how many bits)
  - Satellite constellation parameters (weapons, sensors)
  - Battle management/engagement rules
  - Perception of enemy systems performance
  - Sensor performance data
  - Sensor locations
  - Interceptor performance data
  - Interceptor stockpile/location data
  - The response of all above systems to potential natural or induced environments (this is where nuclear effects are represented)

- Offense (Hostile Forces)
  - Weapon laydown (space and time)
  - Weapon system assignment to friendly forces assets (what type, how many)
  - Actual offensive systems characteristics/performance
  - Tactics (salvage fuzing, etc.)
  - The response of offensive systems performance to potential natural or induced environments.

The majority of the above required information is either able to be quantified or parametrized for use in trade-off studies, but a much higher level of knowledge is required for actual final system configuration and design. Some of the necessary knowledge, however, is very difficult to acquire. One way to deal with such uncertainty is with extensive variation of the unquantifiable parameters, to find out which are the drivers, which are not, and how robust a system must be made to allow for the uncertainty. While this approach is tolerable within limits (if not overused), extensive uncertainty will usually lead to overdesigned systems. An equally dangerous approach is to fix the parameters at some most likely scenario and pursue the analysis from that perspective. Designing about such a point solution can yield a defense that is very vulnerable to surprises.

We believe that one potentially important aspect of fidelity at this level is the representation of prompt nuclear weapon effects (in the form of SEP response). Of course, these cannot possibly be actually simulated in a first principles physics sense, because the requisite run times and array sizes would be unmanageable. Rather, the effects are represented indirectly in the form of system element performance versus parameters that characterize the environment at the SEP location at that time in the simulation. The depth and completeness of understanding of the physics involved and the accuracy of the simulated platform response to the effect are all simulation fidelity issues. Sometimes excessive safety margins are assigned to a particular subsystem to cover for poor understanding of a radiation effects phenomenon or effect, and this is in a sense a fidelity issue. Other examples of simulation fidelity issues are the precise location of the SEP and the detonation point of the enemy warhead.

Simulations at the SOS level are commonly used to determine threat environments for a particular SEP. This highlights the close relationship between survivability and hardening. That is, the point threat for an SEP is determined by asking to what nuclear environment the system element should be hardened to in order to maximize or to insure mission survivability. We also point out that an SOS can be survivable without being intentionally hardened at all. This is because survivability can be attained using a combination of active defense, avoidance, proliferation, reconstitution, deception, and redundancy, as well as hardness.

In the past, SEs and SEPs were less interdependent, and hence survivability was easier to determine and to ensure by requiring element hardness to a specified threat level ("the spec"). That is, formerly SOS survivability could be approached more by hardening the system elements, subsystems, components, and parts. In the future, there will be a shift to an emphasis on mission survivability of complex interdependent systems. Hence it will be important to demonstrate mission survivability of a complex interlaced SOS, and the only way this can be done is via a simulation of the SOS involving code simulation of nuclear environments and effects as well as some (if not most) system elements and their responses.

Another simulation fidelity issue is the issue of uncertainty. The accuracy of simulation results is dependent upon the level of knowledge in the hands of the defense analysts. A very complex simulation might be able to calculate results very precisely but, without quality inputs, the results may not be very accurate. When considering required or desired simulation fidelity, one should balance the detail of the analysis with the level of knowledge that is or can become available. From the viewpoint of the defensive planner, all that can be controlled strictly or known well are the parameters of the defensive system. It may turn out that the parameter space that must be examined can be reduced if we at least make the parts we can know more accurate, e.g., the representation of nuclear effects. This would not be done by actually simulating the effects in the engagement codes, but by ensuring more accurate representation through better characterization in the lower level protocols. Once the issue of simulation balance is decided, it must be determined if the desired detail can be achieved using available computer assets. When assessing systems at this top level, there is currently no possible way to model all low-level components of the system in a first principles sense. Even the System Simulator (the engagement model used at the National Test Bed) running on multiple Cray computers is not capable of handling such detail. The requisite run times and array sizes are simply unmanageable. However, as stated above, such detail would not necessarily lead to significantly more accurate results than if well-constructed approximations are made.

Simplifications and approximations do not reduce the need for complete or accurate physical analysis; rather in order to achieve the balance needed, a solid understanding (or better representation via more accurate fragility curves, for example) of the underlying physical mechanisms and effects is needed. It is a difficult but relatively manageable task (at least computationally) to apply first-principles physics to *individual subsystems, components, and parts*. To be able to consistently and relatively accurately predict, model, and represent SEP responses in a high-level simulation, without extensive use of first principles requires a higher level of expertise and experience. This is one of the main simulation fidelity issue pertaining to survivability validation protocols at the SOS level of integration.

### 3.2 NEXT LOWER LEVEL OF INTEGRATION: THE SE LEVEL.

This level of integration raises all of the same considerations regarding simulations as the SOS level. Indeed, it can be viewed as simply a subset of the SOS level. All of the above considerations apply, except that now the same potential environments apply to all of the individual platforms (although the actual environment levels from a single burst would be different on each). One may ask why survivability protocols would be desirable or needed at this SE level. The answer is that they may make sense because of the desirability of a modular characterization of the SE.

### 3.3 NEXT LOWER LEVEL OF INTEGRATION: THE SEP LEVEL.

In contrast to the SOS or SE, at the SEP level of integration and below, a nuclear environment can be specified in terms of a point environment (i.e., an x-ray fluence, spectrum, and time waveform, a total dose, a neutron fluence, a blast overpressure, an IR irradiance, etc.) that all of the element platform subsystems are subjected to (although shielding, either gratuitous or intentional, will alter some of the environments at the subsystems and components). This is true of both prompt nuclear environments (e.g., x-rays, prompt gammas, neutrons, EMP) and persistent nuclear environments (e.g., IR, debris gamma, betas). Because of this, hardware (physical) simulation of some components of a nuclear environment becomes plausible at the SEP level of integration and below. A "threat" at the SEP level normally means a range of plausible point environments that the SEP may encounter.

The set of nuclear environments affecting a given SEP depends strongly on the basing mode of the SE. That is, whether it is a space based element, a missile, an airframe, or a ground installation. The relevant nuclear environments for these will all be different. For example, a ground installation may be subject to gamma, neutron, EMP, SREMP, blast overpressure, and blackout environments, whereas a space system may be mainly subject to x-rays, neutrons, and IR environments. It is of interest to note that many systems, an ABM defense for example, will involve many of these basing modes linked together to comprise the SOS, and hence there are many combinations of potential environments to be considered.

We emphasize the distinction between nuclear effects and SEP response to a nuclear environment. It is the response that is of ultimate concern to mission survivability. It is also the response that is really represented in an engagement scenario simulation code, even though this is sometimes loosely referred to as "simulating nuclear effects." We define nuclear effects as the physics of the interaction of the nuclear environment with an SEP: electron emission drives currents which burn out or upset electronics, debris gammas cause noise spikes in focal plane arrays, and so on.

Nuclear effects can be considered to be of two general types, those that pose a damage or an upset concern, and those that cause performance degradation, such as reduced S/N ratio in an IR sensor or attenuation in a communication link. Generally, it is the prompt environment that can cause damage or upset, the persistent environment that can cause the S/N and attenuation problems. Thus it is acceptable in a hybrid SOS simulator to physically represent the detectors and sensors that may be subject to a persistent environment (using scene generators to simulate the environment, for example), but it will be more desirable to use software to simulate the element platforms (or subsystems or components) and prompt environments.

Physical simulations (or tests) along with analytic techniques, including codes, models, and simple algorithms comprise the basis of survivability validation protocols at the SEP level of integration and below. In fact, survivability at the platform level is usually implemented by the concept of ensuring survivability to a system element threat through a set of protocols involving test and analysis (at the platform, subsystem, component, and piece part/materials levels of integration). The SE threat is determined by means of simulation (engagement scenario and war gaming) codes, and consists of a set of point environments such as ranges of x-ray fluences and blackbody temperatures, neutron fluences and spectra, EMP levels, and so on. Hence, at the SEP level of integration and below, survivability validation protocols are often synonymous with hardening protocols where the objective is to demonstrate that the SEP or subsystem or component will function satisfactorily to some scenario-determined threat environment (or in some cases to a level representing a generally agreed upon technology limit to hardening). Often, in the past, such protocols only demonstrated pass or fail at a specification level, and did not determine the environment level where failure, upset, or degradation sets in. This is another issue which also affects simulation fidelity at the SOS level, since in reality gradual degradation or a fuzzy failure level is involved.

For some SEPs, AGTs or UGTs can be done on the entire SEP (for a proof test, for example). UGTs presently allow for test articles with dimensions of "tens of feet" or smaller, whereas AGTs, in general, can accommodate larger dimensions, depending on the effect. With regard to UGTs, there are a number of simulation fidelity problems and issues even though the environment is generated by a nuclear detonation, and involves, to a degree, a combined environment (AGTs generally do not). There are many element platforms and many nuclear effects that do not lend themselves to UGTs: some proposed SEPs are too large (some space platforms of 100 meters have been proposed), or the effects to which they are most vulnerable are not present in UGT environments (debris gamma, SREMP, ECEMP, IR, and EMP are examples of environments that may not be present at all or to realistic degrees in UGTs). Also, a UGT affords only one exposure direction, which is a severe simulation fidelity limitation since an x-ray threat, for example, may be incident from any angle (thus, the vulnerability analyst must have correctly assessed the worst case exposure direction for the test to be a completely valid proof test).

In some cases, high fidelity simulations can be done on a representation or a subset of the element platform for some particular nuclear effect. Examples are tests of a complete RV or satellite electrical system in either a UGT or an AGT; a seeker from a ground based interceptor to IR and debris gammas in an AGT; a mockup of the system structure for mechanical effects, either in a UGT or some mechanical effects simulator such as a magnetic flyer. In some cases, scale models are tested, and the results scaled.

For some platforms, such as a radar or those involving a surveillance sensor, e.g., Brilliant Eyes (BE), the combined (hybrid) hardware/software simulation mentioned above can be done. Everything from end-to-end software to end-to-end hardware, e.g., Portable Radiation/Redout Testbed for Sensors (PORTS) can be employed.

An important point here is that only in a UGT can an SEP be exposed to a nuclear detonation environment. However, this high fidelity testing will be limited because of the expense of such tests. Another relevant consideration that can limit the number of these tests is the undesirability of breaking a complex expensive system. It should be noted that the simulation fidelity of a UGT is not perfect (there are issues regarding x-ray pulse width, rise time, spectrum, neutron arrival time, and x-dot to gamma-dot ratios, to give a few examples). Furthermore, persistent nuclear environments are not necessarily present in a UGT (though they can be added with an external source or simulated with a scene generator). Another important issue is that the hardware under test may not be the final design, and hence any simulation will lack fidelity, no matter how well the environment is simulated. Furthermore, careful configuration control between the tested, prototype version and a production unit can permit analysis of expected changes in system hardness and highlight the need, if any, for retests of some systems.

A recent DoD/DOE study has explored capabilities, limitations, and design and effects requirements of physical simulators of nuclear weapon effects. This study, referred to as the above ground experiment (AGEX) study, has recently focused on defining design and effects requirements for the next 10 to 20 years. This second phase (Phase II) is referred to as AGEX II; an earlier phase (Phase I) focused on present AGEX capabilities along with possible new capabilities. The AGEX references listed below[1, 2, 3] provide much more detail on the capabilities and limitation of existing physical simulators.

Code simulations at this level are also limited in fidelity because not all of the various effects due to all of the threat components can be simulated at the same time. Advances in computer technology may not help this to any significant extent. Furthermore, even just a single effect such as SGEMP is very complex, and exists at various levels within a system, so that in practice code simulations and analysis must be done at lower levels and folded together.

### 3.4 THE NEXT LOWER LEVEL OF INTEGRATION: THE SUBSYSTEM LEVEL.

Here virtually all of the points made regarding SEPs still apply, although now UGTs almost always accommodate the size. Furthermore, at this level, present or near term simulators such as DECADE will permit full exposure for many subsystems (a major exception might be some of the power subsystems where the solar panels may be too big). However, the simulation fidelity of the environment can be a major problem. This is especially true for x-ray electrical effects, where it is generally not possible to attain realistic fluences in concert with threat-realistic x-ray spectra, pulse widths, and exposure areas. In particular, a common problem is that for realistic fluence levels, the x-ray spectrum tends to be too hot to accurately simulate all aspects of SGEMP. The primary function of these machines for subsystem testing will continue to be, as it has in the past, for model and analysis verification.

Just as with the system element, a practical fidelity issue regarding tests (physical simulations) at the subsystem level is that often the subsystem itself is not the final design. Because of production schedules and protocol testing schedules, it often cannot be. In some cases, instrumenting the test can raise the issue of whether the subsystem is modified by the test, and this is certainly a fidelity issue. Again, careful configuration control between test items and production units should be employed.

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1. Dr. Paul Senseny, "Technical Report: AGEX II Study Team 6," Defense Nuclear Agency, March 15, 1991, Unclassified.

2. Dr. Wendland Beezhold, "Simulation Technology Programs at Sandia National Laboratories," pages 3 and 9, Nuclear Survivability, DNA, February 1991, Unclassified.

3. "AGEX Capability, Nuclear Weapon Effects in Electronics: 10-20 Year Plan (U)," Team 7 Report, Secret.

## 3.5 THE NEXT LEVEL OF INTEGRATION: COMPONENTS (ELECTRONICS BOXES, STRUCTURAL ELEMENTS, FOCAL PLANE ARRAYS, LENSES, MIRRORS, ETC.).

This has been the level most commonly studied by the radiation effects community. At this level, it is generally the prompt environment which is of concern. UGT phenomenology tests, which support assessment of hardness to a particular effect at higher levels of integration are frequently done, and will continue to be very important (if they are available, i.e., if there is no Comprehensive Test Ban Treaty, or CTBT). Such tests are relatively high fidelity (since the prompt effects are well represented), although a growing movement in the community stresses that these UGTs are simulations (with their own simulation fidelity limitations).

For electronics boxes, CITs to represent prompt electrical effects such as due to SGEMP, SREMP, and EMP are an important part of any hardening protocol at this level. The simulation fidelity limitations for CITs discussed above (in Section 2.2) apply.

Again the fidelity issue of whether the hardware tested is the final design is important. Also such things as electronics states, biases, and optical power levels (for tests on fiber darkening, for example) are fidelity issues, since these can affect the response, and hence care must be taken to see that they are representative of the state during an actual nuclear engagement.

## 3.6 THE LOWEST LEVEL OF INTEGRATION: THE PIECE PART AND MATERIALS LEVEL.

The effects of concern here tend to be localized at the lowest level itself, and hence can be studied and assessed at that level. Examples are TREE in the parts, and radiation effects in materials (e.g., crumbling of teflon at a dose threshold). Other examples are baffle blowoff, radiation induced dielectric conductivity in cable and box dielectrics, impulse loading of heatshields (as a driver in TSR calculations), and fiber darkening. In the case of TREE in piece parts the fidelity is the best (or adequate) since often these effects are not thought to depend on anything but dose rate, for example. Also, established hardening and survivability protocols tend to already exist at these levels.

A key aspect of basic materials tests at this lowest level is that they can be performed on samples of any convenient size (the radiation effects of concern are of an intensive nature rather than extensive). For example, coupons of baffle material can be used to study blowoff.

## SECTION 4

## CONCLUDING DISCUSSIONS

### 4.1 DISCUSSION OF POTENTIAL APPLICATIONS OF AI.

The lack of adequate models for some nuclear environments and some SEP responses is an important simulation fidelity issue in survivability validation at the SOS (and SE) levels of integration. Models may not include sufficient detail or may represent computational bottlenecks when exercising the overall system analysis code. Artificial Intelligence (AI) programming techniques could be an important tool to improve models and reduce computer run time. AI research has been ongoing for about 50 years now, but the field has only matured to the point of widespread practicality in the past decade. Definitions of AI abound, but for the purposes of this paper AI is defined as using a computer to perform a task that is traditionally thought to require human insight or expertise to perform. AI has many subfields with large amounts of current research occurring, but the areas that seem most applicable here are expert systems and artificial neural networks. A related technology that will also be discussed is fuzzy set theory and fuzzy logic.

#### *4.1.1 Expert Systems.*

Expert systems are computer programs that combine rules, facts, and an inferencing system to emulate the decision-making process of an expert. The rules are usually in the form of a declarative IF-THEN statement, such as:

IF RV aeroshell is cracked AND altitude is greater than maximum pressure altitude THEN probability of RV failure equals 0.99.

The facts are simply the values of the variables in the antecedent part of the IF-THEN rule, which are determined in the course of the analysis or entered as input. Once a rule has "fired", and has created or modified the value of a variable in the consequent, that variable can be used in the antecedent part of another rule. The part of the program that matches the facts to the rules and decides which rule to attempt to apply next is referred to as an inference engine. At first glance, it might appear that IF-THEN statements like this are a commonly used part of traditional programming techniques. While this is true, expert systems allow the user to only derive and elucidate the applicable rules, and not have to worry about the order in which the rules are used.

For example, after many years of experience with nuclear effects analysis, an expert might have developed a set of heuristics ("rules of thumb") regarding which effects are most prominent in various regimes. These heuristics could be gathered into an Expert System for a quicker analysis than first principles would produce. While the answers given by the expert system would probably be less accurate, the decrease in required computing resources might actually provide greater fidelity in an SOS level code by allowing for a wider range of studies.

While such a technique holds some promise for tasks such as nuclear effect determination, there are also several drawbacks to this technology that can make it very difficult to implement successfully. First, to create an expert system, one must first have an expert from which to derive the knowledge. Second, the process of deriving the rules for the expert system ("knowledge engineering") is usually a very difficult task. In many case histories of successfully implemented expert systems, one of two things has happened: either the knowledge engineer became a domain expert in the process, or the expert has become a knowledge engineer.

The reasoning behind this is as follows: Expert systems are generally built to perform difficult tasks. For easy tasks, there is little point in expending the considerable effort required to build an expert system. True experts in complex domain areas often are no longer aware of how they perform their decision-making process (that is often what makes them "expert"). Thus the knowledge engineer has to be able to disassemble the expert's compiled knowledge into the set of IF-THEN rules. In doing so, the knowledge engineer often becomes familiar enough with the subject matter to be considered an expert himself. In most successfully constructed expert systems, the knowledge engineer had some knowledge of the domain at hand to begin with. In other cases where the knowledge engineer fails to elucidate the knowledge, the expert has chosen or been forced to learn enough about expert system theory to perform the knowledge engineering.

Regardless of the manner in which the knowledge base is constructed, expert systems are traditionally exercised in a stand-alone mode. That is, most expert systems are interactive programs that ask users a series of questions to arrive at a conclusion. Recent applications, however, have been incorporated in-line with other applications for control or analysis, as would be necessary in the nuclear effects simulation within engagement codes. One final note that is of vital importance: experts sometimes make mistakes. Expert systems can be expected to be no more accurate than human experts and should, therefore, be developed and checked out with great care.

#### *4.1.2 Neural Networks.*

The second potential application of AI to nuclear effects modeling in high-level war-gaming codes is through the use of artificial neural networks. Simply stated, neural nets perform their various tasks by learning by example, much as learning takes place in the human brain. The nets are trained by being shown numerous examples of various input combinations leading to different results. As the neural net "trains" on these data, it learns that different combinations of input values taken together imply certain output states. In AI lexicon, the synaptic connections between neurons are strengthened when the neurons fire simultaneously, allowing minimum energy paths to evolve based on distinct states of input neuron sets.

Artificial neural networks are very good at working with numeric data. One of the simplest applications of neural nets is for multi-dimensional numeric interpolation. In the arena of nuclear weapons environments and effects, for example, a large number of nuclear environments and response code runs could be made to create a spanning set of expected conditions and resultant responses. The resulting data set could be trained into a neural network and a stand-alone program could be created to estimate the effects without explicitly calculating the environments. For use in a high level simulation, neural net source code could also be created for in-line inclusion with traditional or existing code. For applications such as these, where the first principles codes are very complex and computer-intensive, run-times for the environment/effects modules could be expected to diminish by as much as several orders of magnitude. The advantage to neural nets over look up tables is their ability to generalize and perform limited extrapolation as well as interpolation. Also, neural nets can usually be trained with less data than a look up table would require. For example, neural nets can automatically deduce the proper scaling methods (linear, exponential, etc.), while the hard coded table look up routines may not catch all the proper methods. This allows neural nets to operate with better behavior between data points and often allows the nets limited prediction capabilities beyond the scope of the original data.

Other applications of neural nets here include pattern recognition. As long as the neural net programmer can identify all meaningful input parameters (neurons), the neural net will find many underlying patterns that might escape the scrutiny of humans. This is due to the neural net's inherent capability to organize vast amounts of numeric data as opposed to humans' tendency toward symbolic data manipulation.

While neural nets usually offer their results with astonishing speed, one must be able to accept a penalty in terms of precision. The outputs of neural nets are usually approximations of what a physics or engineering code would produce. Neural nets are ideal technology candidates when a quick, good answer is preferable to a slow, near-perfect result. This brings us full circle to the question of uncertainty and balancing accuracy against precision. In modeling a system where uncertainty in the inputs will by definition lead to a loss of accuracy, the precision afforded through artificial neural networks may well prove sufficient.

Again, it is important that a domain expert play a big role in training the neural net since properly selected data must be used to train and test the neural net. It is also necessary to have a neural net expert involved, since he is required to train the neural net, and knows the neural nets limitations.

### *4.1.3 Fuzzy Logic.*

A related technology that has potential applications within both expert systems and neural networks is fuzzy logic. Fuzzy logic and fuzzy set theory define a very powerful way to treat uncertainty in many systems. The concept underlying this recent technology development is that of partial set membership. Traditional set theory states that an object is either a member of a set, or it is not. Fuzzy set theory allows an object to be a partial member of a set. For example, consider the imprecise concept of whether a nuclear warhead is large or small. Clearly, a ten megaton warhead would be a member of the set of large warheads. Similarly, a fifty kiloton warhead could safely be considered to be small. But what about a 300 kiloton yield? Fuzzy set theory would allow, for example, sixty percent membership in the small warhead set and forty percent in the large. Traditional set theory operations have also been modified to allow familiar set manipulations on fuzzy sets (union, intersection, etc.).

Fuzzy sets have great potential in creating expert systems that deal with uncertain data. For instance, rather than creating an IF-THEN rule with numeric values in the precedent (IF warhead yield is greater than 1 megaton. . .), a rule could test for an imprecise concept (IF warhead yield is relatively large. . .). Thus if the U.S. were not able to ascertain the exact characteristics of a potential threat, it could still be addressed with approximate or vague data. The application of fuzzy logic to neural networks is less explicit. The very concept behind neural nets allows for uncertainty and approximation. The values of partial set membership (usually between zero and one, inclusive) could be easily included in the set of input neurons (that is, the list of input parameters) for a neural network.

The primary task in creating a fuzzy set is defining the level of set membership for various objects. For example, one might create a linear function for warhead "largeness" that starts with non-zero membership at 100 kilotons and gains complete membership at two megatons. Nonlinear functions are also commonly used in fuzzy set membership definitions.

The preceding paragraphs might seem to imply that the uncertainties involved with the threat definitions preclude the use of traditional first-principles physical models in simulations. This is not the case. Rather, several technologies are emerging that allow efficient approximations of important effects to be made. However, these new techniques are wholly dependent upon the availability of accurate data for use in the various approximations. If there is not a database of correct and complete low-level effects available, then these approaches will not yield valid approximations.

## 4.2 DISCUSSION OF OTHER SIMULATION FIDELITY ISSUES.

One obvious point is that for end-to-end SOS validation, it is desirable to include as much of the actual hardware and man-in-the-loop as possible (at least in some of the simulations). A related point here is that the hardware (element, subsystem, etc.) raises simulation fidelity issues. Sometimes it is available only in a prototype form. Or, in tests at the system level and below it is instrumented in a manner which can affect its response. Sometimes the hardware can exist in several possible (functional) states, and it may be important to consider and represent all or many of them to get good fidelity (i.e., a good representation of the way an element will respond).

Furthermore, the representation of nuclear environments and effects (in the form of element response to the environment) is crude in presently available engagement codes, and it is possible that in upgrading them (improving the fidelity ) better survivability validation could be done. The question is, where do uncertainties and fidelity limitations have the largest impact on the results. The need for better characterization of element response to a nuclear environment will put a demand on the protocols at the element level (and below) to come up with more extensive characterization of nuclear effects (in the form of fragility curves, for example).

Even if there are great uncertainties in certain aspects of the SOS software models, for example the enemy capabilities and responses, the number and degree of parameter variations could perhaps be reduced if we minimize uncertainties in aspects that we understand and where it makes a difference. In particular, inaccuracies in survivability assessment due to inaccuracies in the representation of nuclear effects can be reduced by representing them with higher fidelity in the SOS simulations (whether purely software or hybrid). This does not mean that the effects should actually be simulated as such in the engagement models, but rather that they should be more comprehensively and more subtly represented (via more accurate fragility curves, for example). By more comprehensively, we mean that all important effects are considered; at present, it is common to include only one or two, and the person doing the simulation may not have any idea or understanding of what the most stressing effects are. This means that not only must the nuclear effects be thoroughly understood at the lower levels of integration (and there are still gaps in our knowledge), but that procedures should be established to formulate the effects at the element level and pass them on in a form the SOS simulation designers can use.

Electrical system representations of system elements could be used as part of the survivability protocol: It can be used to validate the survivability at the element level to an identified worst case x-ray threat. (This is an electronics proof test). By preserving the essential electrical configuration but not the geometry and element platform structures, the test volume and requisite exposure area can be greatly reduced, and simulators with exposure areas like those envisioned for DECADE could be used for some systems. The justification for this kind of test is that electrical systems are routinely designed so that cable SGEMP and box IEMP are the predominant x-ray (or gamma-ray) induced electrical effects at the pin and board levels. In particular, EMP, external SGEMP, and cavity IEMP are usually rendered negligible at the pin and board levels by virtue of the shielding effectiveness of the cable and box RF shielding. Such a test can be done with a UGT or an AGT. However, AGTs have many advantages, such as convenience and lower expense, and in the long run may be the only kind of test available. One advantage is that AGTs afford a chance to expose the element from many directions (direction is a simulation fidelity issue, and here UGTs are poor). There are limitations in existing and planned simulators, however, such as spectrum and rise times of the x-rays. Some of these could be overcome by innovative strategies for simulating, matching, or correlating responses. An example is using a higher response element, such as an unfilled cable or a Compton diode, to represent the response of a filled cable with better fidelity (the response per fluence in DECADE will be much smaller than to threat x-rays for a given cable type).

An area of subsystem testing that will be important for future SOSs involving IR sensors are hybrid simulations of combined prompt and persistent environments. It is possible to do what is essentially end to end hardware testing of optical sensors by using scene generators to simulate targets and the persistent IR background, and using an AGT facility or a UGT to provide prompt environments and simulation of debris gamma. PORTS is an example of this concept. Such concepts raise a host of fidelity issues, such as how well debris gammas are simulated, how well the IR and targets are simulated, how well baffle blowoff is simulated, and how well box IEMP and TREE are represented.

## APPENDIX

## GLOSSARY

| | |
|---|---|
| ABM | Antiballistic Missile |
| AGEX | Aboveground Experiment |
| AGT | Aboveground Test |
| AI | Artificial Intelligence |
| $C^2$ | Command and Control |
| CIT | Current Injection Test |
| CM | Countermeasures |
| CTBT | Comprehensive Test Ban Treaty |
| DNA | Defense Nuclear Agency |
| ECEMP | Electron Caused Electromagnetic Pulse |
| EMP | Electromagnetic Pulse |
| GPALS | Global Protection Against Limited Strikes |
| IEMP | Internal Electromagnetic Pulse |
| IR | Infrared |
| LIHE | Light Initiated High Explosive |
| MILSTAR | Military, Strategic and Tactical Relay satellite |
| NTB | National Test Bed |
| PORTS | Portable Radiation/Redout Testbed for Sensors |
| RV | Reentry Vehicle |
| SDI | Strategic Defense Initiative |
| SE | System Element |
| SEP | System Element Platform |
| SGEMP | System Generated Electromagnetic Pulse |
| S/N | Signal-to-Noise Ratio |
| SOS | System of Systems |
| SREMP | Source Region Electromagnetic Pulse |
| SV | Survivability Validation |
| TMD | Theater Missile Defense |
| TREE | Transient Radiation Effects in Electronics |
| TSR | Thermostructural Response |
| UGT | Underground Test |
| VN | Vulnerability Numbers |

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ATTN: SLCHD-NW-TN R LINGEBACH
ATTN: SLCHD-NW-TS
ATTN: SLCHD-RI
ATTN: SLCHD-RP
ATTN: SLCHD-TL-WRF
ATTN: SLCHD-TN
ATTN: SLCIS-IM-TL
ATTN: SLCSM-AA D ROBERTS
ATTN: SLCSM-D COL J DOYLE

HOWITZER IMPROVEMENT PROGRAM
ATTN: AMCPM-HIP J CARBONE

JOINT TACTICAL FUSION PROG OFFICE
ATTN: DAMO-FDJ
ATTN: G SHINER
ATTN: JTFPO-DIC

JOSEPH J WIEDMANN
ATTN: AMSEL-RD-NV-STDD-IRCT

MINES, COUNTERMINES & DEMOLITIONS
ATTN: AMCPM-MCD-D

MOBILE ELECTRIC POWER
ATTN: PROJECT MANAGER

OFFICE OF ASSISTANT SECRETARY OF ARMY
ATTN: DAMA-PPM
ATTN: SARD-TR
ATTN: SARD-ZCS

OFFICE OF THE PROJECT MANAGER
ATTN: AMCPM-ABMS
ATTN: AMCPM-GCM-SW M PATTISON
ATTN: AMCPM-GCM-SW L DICK
ATTN: AMCPM-LAV-E NELSEN
ATTN: AMCPM-M1A1 G HOWE
ATTN: AMCPM-M60
ATTN: AMCPM-PG R KEITH
ATTN: AMCPM-SS COL MILLER
ATTN: AMSTA RSK G WOLFE
ATTN: PM ARMORED COMBAT VEHICLE TECH
ATTN: PM BRADLEY FIGHTING VECHICLE SYS
ATTN: PM COMMERICAL CONST EQUIP
ATTN: PM HEAVY EQUIPMENT TRANSPORT
ATTN: PM HEAVY TACTICAL VEHICLES PROV
ATTN: PM IMPROVED VEHICLE READINESS
ATTN: PM LIGHT ARMORED VEHICLES
ATTN: PM LIGHT TACTICAL VEHICLES PROV
ATTN: PM MEDIUM TACTICAL VEHICLES PROV
ATTN: PM MOBILE PROTECTED GUN PROV
ATTN: PM M9 ARMORED CMBT EARTH MOVER
ATTN: PM TACTICAL VEHICLES PROV
ATTN: SFAE-ASM-AG-Q M PETROSKI
ATTN: SFAE-ASM-CV B BONKOSKY
ATTN: SFAE-CS-TVM J HRETZ

PERSHING SYSTEM
ATTN: V KEARNS
ATTN: PROJECT MANAGER

SMOKE/OBSCURANTS
ATTN: AMCPM-SMK

SURGEON GENERAL
ATTN: MAJ W KLENKE DASG-HCD

TANK MAIN ARMAMENT SYSTEM
ATTN: PROJECT MANAGER

U S ARMY AEROMEDICAL RESEARCH LABORATORY
ATTN: COMMANDER
ATTN: SGRD-UAS-NB
ATTN: SIC

U S ARMY AIR DEFENSE ARTILLERY SCHOOL
ATTN: ATSA-CD

U S ARMY ARMOR CENTER AND SCHOOL
ATTN: ATSD-CD-ML
ATTN: ATZK-CD-AA
ATTN: DCD USAARMCIS

U S ARMY ATMOSPHERIC SCIENCES LAB
ATTN: SLCAS-AE

U S ARMY AVIATION CTR & FT RUCKER
ATTN: ATZQ-CDC-CO
ATTN: ATZQ-CDM-A
ATTN: ATZQ-CDM-S
ATTN: ATZQ-DPT-P
ATTN: ATZQ-TDS-AS S STONE
ATTN: ATZQ-TSM-S

U S ARMY AVIATION SYSTEMS CMD
ATTN: AMCPM-AAH-SEG J ROMANO
ATTN: AMCPM-ASE-APM
ATTN: AMCPM-CO
ATTN: AMCPM-LHX W MORTON
ATTN: AMCPM-LHX-TU F MOKRY
ATTN: AMSAV-ES LTC DEVAUGHAN
ATTN: AMSAV-ESE D ALBRIGHT
ATTN: AMSAV-MEM SYED AHMAD
ATTN: AMSAV-NS C KRILL
ATTN: AMSAV/ES SFC PEARSON
ATTN: COMMANDER
ATTN: PM ADVANCED ATTACK HELICOPTER
ATTN: PM AIRCRAFT SURVIVABILITY EQUIP
ATTN: PM APACHE AUTOMATIC TEST EQUIP
ATTN: PM ARMY HELI IMPROVEMENT PGM
ATTN: PM BLACKHAWK
ATTN: PM CH-47 MODERNIZATION PROGRAM
ATTN: PM LIGHT HELICOPTER FAMILY PROV
ATTN: PM TACT AIRBORNE RPV/DRONE SYS

U S ARMY BALLISTIC RESEARCH LAB
ATTN: SLCBR-SS-T
ATTN: SLCBR-TB-B J POLK
ATTN: SLCBR-TB-B R RALEY
ATTN: SLCBR-TB-S W P WRIGHT
ATTN: SLCBR-VL-A A M VOGEL
ATTN: SLCBR-VL-S DR J MORRISSEY

U S ARMY BELVOIR RD&E CTR
ATTN: STRBE-FGM
ATTN: STRBE-FGP HUNGATE
ATTN: STRBE-H WEN H CHEN

U S ARMY CHEMICAL RSCH & DEV CTR
ATTN: SMCCR-DDP
ATTN: SMCCR-MSI
4 CYS ATTN: SMCCR-NB
ATTN: SMCCR-PPC
ATTN: SMCCR-PPS

U S ARMY CORPS OF ENGINEERS
ATTN: DAEN-ZCM

U S ARMY CORPS OF ENGINEERS
ATTN: CEMRO-ED-SW W GAUBE

U S ARMY ELECTRONIC RESEARCH & DEV CMD
ATTN: PROJECT MANAGER

U S ARMY ENGINEER DIV HUNTSVILLE
ATTN: HNDED-CS

U S ARMY ENGR WATERWAYS EXPER STATION
ATTN: CEWES-IM-MI-R/A S CLARK
2 CYS ATTN: WESGH
2 CYS ATTN: WESGR
2 CYS ATTN: WESSD
2 CYS ATTN: WESSE
2 CYS ATTN: WESSS

U S ARMY FOREIGN SCIENCE & TECH CTR
ATTN: AIFMI LIBRARY
ATTN: AIFOC
ATTN: AIFREA
ATTN: AIFRTA

U S ARMY INFANTRY CENTER
ATTN: ATSH-AC
ATTN: ATSH-CD-MLS

U S ARMY JOHN F KENNEDY SPECIAL WARFARE CTR
ATTN: ATSU-CD-ML
ATTN: ATSU-DT-TMD

U S ARMY LABORATORY CMD
ATTN: COMMANDER

U S ARMY LABORATORY CMD INSTL SUPP ACTIVITY
ATTN: AMSLC-SO
ATTN: SLCIS-D

U S ARMY LABORATORY COMMAND
ATTN: SLCHE-DD

U S ARMY MATERIAL COMMAND
3 CYS ATTN: AMCCN
ATTN: AMCDE-PM
ATTN: AMCIM-SP
ATTN: OFFICE OF PROJECT MANAGEMENT

U S ARMY MATERIAL TECHNOLOGY LABORATORY
ATTN: COMMANDER
ATTN: DRXMR-HH
ATTN: SLCMT-BM
ATTN: SLCMT-OMM

U S ARMY MISSILE & SPACE INTELLIGENCE CENTER
ATTN: AIAMS-YRP BELCHER

U S ARMY MISSILE COMMAND
ATTN: AMCPM-CC-TM-SE
ATTN: AMCPM-CF-T
ATTN: AMCPM-HA-SE-MS
ATTN: AMCPM-HAER
ATTN: AMCPM-HD
ATTN: AMCPM-HD-G
ATTN: AMCPM-HDE
ATTN: AMCPM-ML
ATTN: AMCPM-RP-E
ATTN: AMSMI-RD-CS-R
ATTN: AMSMI-RD-ST-NB
ATTN: AMSMI-RD-TE-C-EM
ATTN: AMSMI-RD-TE-S
ATTN: PM/TO

U S ARMY MISSILE COMMAND
ATTN: MAJ R LUSHBOUGH

U S ARMY MISSILE COMMAND
ATTN: R LENNING

U S ARMY NUCLEAR & CHEMICAL AGENCY
ATTN: MONA-AD
ATTN: MONA-NU
ATTN: MONA-NU DR D BASH
ATTN: MONA-SU

U S ARMY ORD MISSILE & MUNITIONS
ATTN: ATSK-MS

U S ARMY RESEARCH DEV & ENGRG CTR
6 CYS ATTN: STRNC-UE J FANUCCI
ATTN: TECH LIB

U S ARMY SIGNAL CTR & FT GORDON
ATTN: ATZH-CDC S&A BR
ATTN: ATZH-CDM CSS BRANCH

U S ARMY SIGNAL WARFARE CTR VHFS
ATTN: AMSEL-SW-MA

U S ARMY STRATEGIC DEFENSE CMD
ATTN: CSSD-CS
ATTN: CSSD-OP
ATTN: CSSD-SA-E

U S ARMY STRATEGIC DEFENSE CMD
ATTN: CSSD-H-LS
ATTN: CSSD-SD-A

U S ARMY STRATEGIC DEFENSE COMMAND
ATTN: CSSD-SA-EV
ATTN: CSSD-SA-EV R CROWSON
ATTN: CSSD-SL
ATTN: SFAE-SD-GST-E P BUHRMAN

U S ARMY TEST & EVALUATION COMMAND
ATTN: AMSTE-TA-F
ATTN: AMSTE-TA L TELETSKI

U S ARMY TRAINING AND DOCTRINE COMD
ATTN: ATCD-N

U S ARMY TROOP SUPPORT COMMAND
ATTN: AMSTR-E
ATTN: AMSTR-E A CHRISTENSEN
ATTN: AMSTR-E MAJ MERRYMAN
ATTN: AMSTR-WN L DOMITZ
ATTN: PM AMPHIBIANS & WATERCRAFT
ATTN: PM PETROLEUM & WATER SYSTEMS

U S ARMY VULNERABILITY ASSESSMENT LAB
ATTN: SLCVA-D

U S ARMY VULNERABILITY/LETHALITY
ATTN: AMSLC-BL-N BASSETT
ATTN: AMSLC-VL-NE DR J FEENEY

US ARMY COMMUNICATIONS-ELECTRONICS CMD
ATTN: AMCPM-COM-RN-B
ATTN: AMCPM-GARS-TMD
ATTN: AMCPM-JS-TM
ATTN: AMCPM-MSCS-PM
ATTN: AMCPM-PL
ATTN: AMSEL-RD-ASCO C KELLINGTON

ATTN: AMSEL-RD-EN-SS GROEBER
ATTN: COMMANDER, R&D CENTER
ATTN: PM FIELD ARTY TACT DATA SYS
ATTN: PM FIREFINDER REMBASS
ATTN: PM OPERATIONS TAC DATA SYS
ATTN: PM SATELLITE COMMUNICATIONS
ATTN: PM TEST MEASUREMENT & DIAG EQUIP

US ARMY ELEMENT
3 CYS ATTN: CHIEF NCOPS

US ARMY MATERIEL COMMAND SUPPORT ACTIVITY
ATTN: AMXTB-D W P WYNBELT

US ARMY MATERIEL SYS ANALYSIS ACTVY
ATTN: AIFIF
ATTN: AMXSY-CR D SMOOT
ATTN: AMXSY-GS

US ARMY ORD MISSILE & MUNITIONS CTR & SCHOOL
ATTN: ATSK-CC BILL GREEN
ATTN: ATSK-CCU
ATTN: ATSK-CM
ATTN: ATSK-CMA
ATTN: ATSK-CML
ATTN: ATSK-CMM
ATTN: ATSK-CT
ATTN: ATSK-E R F PENDLETON
ATTN: ATSK-M
ATTN: ATSK-Z
ATTN: CW4 FRANK L PRABEL III

USA ELECT WARFARE/SEC SURV & TARGET ACQ CTR
ATTN: AMSEL-EW-MD
ATTN: AMSEL-EW-SS S KRONENBERG
ATTN: COMMANDER

USA SURVIVABILITY MANAGMENT OFFICE
ATTN: AMSLC-VL-NE DR J FEENEY
ATTN: F MANION
ATTN: SLCSM-SE J BRAND

USACACDA
ATTN: ATZL-CAD-N

V CORPS
5 CYS ATTN: AETV-AT-FSE
2 CYS ATTN: AETV-NBC

VINT HILL FARM STATION
ATTN: G LEE DELCE-PA-EN
ATTN: GEORGE MANDZYCH
ATTN: RICHARD D RIDGLEY

3RD ARMORED DIVISION
2 CYS ATTN: AETV-TF-NBC
2 CYS ATTN: AETV-TFC-FSE

431 CHEMICAL DETACHMENT
ATTN: COMMANDING OFFICER

66TH MI BDE(RDA)
ATTN: SECURITY OFFICE

78TH DIV MTC
ATTN: MAJ J EFFINGER

**DEPARTMENT OF THE NAVY**

ASSISTANT CHIEF OF STAFF 6-6
ATTN: CODE C-3B (CEO/E3)
ATTN: COMM-ELECTRONICS OFFICER
ATTN: WEAPON EMPLOYMENT OFFICER

ATKRON
ATTN: LCDR C NUTTER

BUREAU OF MEDICINE & SURGERY
ATTN: MED-212

CHIEF OF NAVAL OPERATIONS
ATTN: OP-07EG ACQUISITIONS UNIT

CINCLANTFLT
ATTN: CODE N4371 P HARNEY

CINCPAC
ATTN: J55

DAVID TAYLOR NAVAL RESEARCH CENTER
ATTN: CODE 770
ATTN: COMMANDER
ATTN: IB S MANSEN
ATTN: J KREZEL

DAVID TAYLOR RESEARCH CENTER
ATTN: CODE 522
ATTN: D MAYO
ATTN: STRUCTURES DEPT

DEPARTMENT OF THE NAVY
ATTN: CODE SEA-61
3 CYS ATTN: COMMANDING OFFICER
ATTN: J GANN
ATTN: PMS-312
ATTN: PMS-300
ATTN: PMS-313T
ATTN: PMS-350
ATTN: PMS-377
ATTN: PMS-383
ATTN: PMS-393
ATTN: PMS-395
ATTN: PMS-396
ATTN: PMS-400
ATTN: PMS-400 F YARBROUGH
ATTN: PMS-402
ATTN: PMS-407
ATTN: PMS-412
ATTN: PMS-413
ATTN: PMS-414-2
ATTN: PMS-415
ATTN: PMS-416
ATTN: PMS-423
ATTN: PMS-423B
ATTN: PMS-423X
ATTN: PMS-4232
ATTN: PMS-4233
ATTN: PMS-4234
ATTN: PMS-4235
ATTN: PMS-303
ATTN: S WONG
ATTN: SEA 56D5 ROLF KOTACKA

ATTN: SEA-00
ATTN: SEA-05
ATTN: SEA-05R
ATTN: SEA-05R2
ATTN: SEA-05R4
ATTN: SEA-06
ATTN: SEA-06AR11
ATTN: SEA-08
ATTN: SEA-501
ATTN: SEA-502
ATTN: SEA-504 J SNYDER
ATTN: SEA-506
ATTN: SEA-55WI
ATTN: SEA-55X
ATTN: SEA-55X1
ATTN: SEA-55X2
ATTN: SEA-56Z
ATTN: SEA-61X33
ATTN: SEA-61Z21
ATTN: SEA-62Z31D C WHEELER
ATTN: SEA-622
ATTN: SEA-63
ATTN: SEA-91
ATTN: SEA-913B1
ATTN: SEA-92
ATTN: SEA-93
ATTN: 61Y12

DEPARTMENT OF THE NAVY
ATTN: DIRECTOR
ATTN: JCM-04
ATTN: JCMG-707

FIGHTER WING 1
ATTN: CODE 34 FOWLKES

FLEET AIR RECONNAISSANCE SQDRN FOUR (VQ-4)
ATTN: LCDR H TROTTER

GPS NAVSTAR JOINT PROGRAM OFFICE
ATTN: CHARLES TABBERT

MAGTF WARFIGHTING CENTER (WF 11C)
ATTN: MAJ C MEYER

MARINE AVIATION DETACHMENT
ATTN: CODE 8000 MAJ C MCSPADDEN

MARINE CORPS
ATTN: AP
ATTN: APW-1
ATTN: APW-41
ATTN: CODE POR-21

MARINE CORPS LOGISTICS BASE
ATTN: 841-3 K MOHL

MARINE CORPS R&D ACQUISITION COMMAND
ATTN: CODE PSA CAPT G MISLICK

MARINE CORPS RESEARCH, DEVELOPMENT
ATTN: CODE PSE-C S BELLORA

MAWTS-1 MCAS
ATTN: MAJ G SARES

NAVAL AIR DEVELOPMENT CENTER
ATTN: CODE 4041 N ANTONINI
ATTN: CODE 60C7
ATTN: CODE5021/MATD G PIRRUNG

NAVAL AIR SYSTEMS COMMAND
2 CYS ATTN: AIR 530T
ATTN: AIR-5115J G T SIMPSON
ATTN: AIR-5164
ATTN: AIR-5164B
ATTN: AIR-5164C
ATTN: AIR-536T DR L E SLOTER
ATTN: AIR-53634D D CALDWELL
ATTN: AIR-93
ATTN: AIR-93D
ATTN: AIR-931
ATTN: AIR-931F L WITHERS
ATTN: JTCG/AS CENTRAL OFC
ATTN: PMA-234
ATTN: PMA-235
ATTN: PMA-239
ATTN: PMA-240
ATTN: PMA-241
ATTN: PMA-242
ATTN: PMA-244
ATTN: PMA-257
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ATTN: PMA-264
ATTN: PMA-265
ATTN: PMA-266
ATTN: PMA-268
ATTN: PMA-270
ATTN: PMA-271
ATTN: PMA-272
ATTN: PMA-275
ATTN: PMA-276
ATTN: PMA-278
ATTN: PMA-279

NAVAL AIR TEST CENTER
ATTN: CODE SY 82A L RAVDURG
ATTN: FW522MB MICHAEL BRECKAN
ATTN: NADOC-743 A HOCH
ATTN: NADOC-743 C GUY
ATTN: RW-82 P BABUCHIWSKI
ATTN: RW-83
ATTN: SY80
ATTN: SY84 SAM FRAZIER

NAVAL AIR WARFARE CTR AIRCRAFT DIVISION
ATTN: PE 34 F HUSTED

NAVAL AVIATION DEPOT
ATTN: CODE 334

NAVAL AVIATION DEPOT
ATTN: CODE 310B M BERRY

NAVAL AVIATION DEPOT ALAMEDA
ATTN: F LACHENMEIER CODE 05211

NAVAL AVIATION LOG CTR DET WEST
ATTN: CODE 31363
ATTN: CODE 7412

NAVAL AVIONICS CENTER
ATTN: B/710 F GAHIMER
ATTN: B/713 D PAULS

NAVAL CIVIL ENGINEERING LABORATORY
ATTN: CODE L64 LORY
ATTN: CODE L51 J FERRITTO
ATTN: CODE L51 R ODELLO
ATTN: SYSTEMS DIVISION

NAVAL COASTAL SYSTEMS CENTER
ATTN: COMMANDER
ATTN: TECHNICAL LIBRARY

NAVAL ELECTRONICS ENGRG ACTVY, PACIFIC
ATTN: CODE 250

NAVAL EXPLOSIVE ORD DISPOSAL TECH CENTER
ATTN: TECH LIBRARY

NAVAL OCEAN SYSTEMS CENTER
ATTN: CODE 6202 J HOLZMANN
ATTN: CODE 824 W KORDELA
ATTN: CODE 824 L SHUTE
ATTN: CODE 824 F W SHAW
ATTN: CODE 825
ATTN: LIBRARY CODE 9642

NAVAL PLANT REPRESENTATIVE OFFICE
ATTN: CODE SPL-336 R HESS

NAVAL POSTGRADUATE SCHOOL
ATTN: CODE 1424 LIBRARY
ATTN: PHYSICS DEPT PROF K WOHLER
ATTN: PROF ROBERT BALL CODE AA/BP

NAVAL RESEARCH LABORATORY
ATTN: CODE 2627 TECH LIB
ATTN: CODE 4600 D NAGEL
ATTN: CODE 4613 A B CAMPBELL
ATTN: CODE 6180
ATTN: CODE 6303 R GULARTE
ATTN: CODE 6550 M PAULI
ATTN: CODE 6800

NAVAL SHIP WEAPON SYSTEMS ENGRG STATION
ATTN: CODE 4T23 H POKORNY

NAVAL SPACE COMMAND
ATTN: CODE VN313 J TRAMMEL

NAVAL SURFACE WARFARE CENTER
ATTN: CODE H 20 K ENKENHUS
ATTN: CODE H-21 W EMBERSM
ATTN: CODE H21 D LYNCH
ATTN: CODE H21 G RUBIN
ATTN: CODE H23 J PARTAK
ATTN: CODE H23 R SMITH
ATTN: CODE H23 S DOUGLAS
ATTN: CODE H23 JEFF KING
ATTN: CODE H23 R PERSH
ATTN: CODE H25 E CARROLL
ATTN: CODE H25 K CAUDLE
ATTN: CODE R14 R BARASH
ATTN: CODE R15
ATTN: CODE R44 R FERGUSON
ATTN: CODE R44 P COLLINS
ATTN: H23
ATTN: M J TINO CODE H
ATTN: WO/H-21 D TOMAYKO
ATTN: WO/H25 N STETSON

NAVAL SURFACE WARFARE CENTER
ATTN: CODE G13 B STROTHER
ATTN: CODE H33 M POMPEII
ATTN: COMMANDER

NAVAL SURFACE WEAPONS CENTER
ATTN: MAJ M PLUMER

NAVAL WAR COLLEGE
ATTN: CODE E-111

NAVAL WARFARE ASSESSMENT CENTER
ATTN: CODE 12A
ATTN: CODE 34W
ATTN: DOCUMENT CONTROL

NAVAL WEAPONS CENTER
ATTN: LETH T ANDERSON
ATTN: CODE 3181 B KOWALSKY
ATTN: CODE 3181 T BELL
ATTN: CODE 3181 DRIUSSI
ATTN: CODE 32
ATTN: CODE 3433 B BABCOCK
ATTN: CODE 39104
ATTN: CODE 3917

NAVAL WEAPONS EVALUATION FACILITY
ATTN: CODE 20 S MAUK
ATTN: CODE 22 RAY C TERRY
ATTN: CODE 224 A ALDERETE

NAVAL WEAPONS STATION
ATTN: CODE 323 M BUCHER

NAVSEA
ATTN: J SATIN

NEW LONDON LABORATORY
ATTN: CODE 31 D BROWNING
ATTN: CODE 3431 J ORR
ATTN: COMMANDING OFFICER
ATTN: TECH LIBRARY

NR PMS TNW 106
ATTN: CAPT DONALD ALF

NUCLEAR WEAPONS TNG GROUP, ATLANTIC
ATTN: CODE 22 LCDR WALKER

NUCLEAR WEAPONS TNG GROUP, PACIFIC
ATTN: CODE 3232
ATTN: CODE 50

NUCLEAR WEAPONS TRAINING UNIT 106
ATTN: DOCUMENT CONTROL

OFFICE OF CHIEF OF NAVAL OPERATIONS
ATTN: CNO EXECUTIVE PANEL OP-OOK
ATTN: OP 02
ATTN: OP 022
ATTN: OP 04
ATTN: OP 05
ATTN: OP 06
ATTN: OP 62
ATTN: OP 654
ATTN: OP 70
ATTN: OP 73
ATTN: OP 74
2 CYS ATTN: OP-65D
ATTN: OP-955
3 CYS ATTN: OPO3C2
ATTN: OP21
ATTN: OP21T
ATTN: OP22T
4 CYS ATTN: OP224
ATTN: OP505F
ATTN: OP76

OFFICE OF CHIEF OF NAVAL OPERATIONS
ATTN: OP-65 LCDR G HERBERT JR
ATTN: OP-65D DR J WEINSTEIN
ATTN: OP-65D LCDR M SEELINBINDER
ATTN: OP-955
ATTN: OP-981

OFFICE OF NAVAL RESEARCH
ATTN: CODE OCNF-10P5
ATTN: CODE OCNR-1114
ATTN: CODE OCNR-1114SE
ATTN: CODE OCNR-1114SP
ATTN: CODE OCNR-1114SS
ATTN: CODE OCNR-12
ATTN: CODE OCNR-12D
ATTN: CODE OCNR-121
ATTN: CODE ONCR-00F
ATTN: CODE ONCR-10E
ATTN: CODE ONCR-10P4
ATTN: CODE ONCR-10P6
ATTN: CODE ONCR-111
ATTN: CODE ONCR-111D
ATTN: CODE ONCR-1112A1
ATTN: CODE 1112
ATTN: CODE 1132SM

OFFICE OF THE SECRETARY OF NAVY
ATTN: CP5

OFFICE OF THE SECRETARY OF THE NAVY
ATTN: SPEC ASST SAFETY & SURVIVABILITY

OPERATIONAL TEST & EVALUATION FORCE
ATTN: COMMANDER

OPERATIONAL TEST & EVALUATION FORCE,
ATTN: COMMANDER
ATTN: DEPUTY COMMANDER

SCIENCE & TECHNOLOGY LIBRARY
ATTN: CODE 202.13

SPACE & NAVAL WARFARE SYSTEMS CMD
ATTN: PD-40
ATTN: PMW 156-13A
ATTN: PMW-142
ATTN: PMW-145
ATTN: PMW-146
ATTN: PMW-147
ATTN: PMW-151
ATTN: PMW-152
ATTN: PMW-153
ATTN: PMW-180-21

STRATEGIC SYSTEMS PROGRAM
ATTN: SP-113 D ELLINGSON

SUPERVISOR OF SHIPBUILDING
ATTN: CMDR OFFICER CG-68 CAPT HOWARD
ATTN: CODE 290 C BARDSLEY

US MARINE CORPS E3 PROGRAM OFFICE
ATTN: K MOHL CODE 841-4

USCINCPAC
ATTN: J6 LTC ROLLER
ATTN: MR HAUT J55

11TH SPECIAL FORCES GROUP A
ATTN: CW4 J PRICE

**DEPARTMENT OF THE AIR FORCE**

AERONAUTICAL SYSTEMS DIVISION
ATTN: ASD/ENACE
ATTN: ASD/ENSSE MR PEPPER
ATTN: ASD/ENSSS
ATTN: ASD/RWWI

AF SPACE COMMAND
ATTN: LKNIP MAJ S HOFF
ATTN: SM-ALC DET 25 P C LARTER
ATTN: DOCE

AFOEHL/RZ
ATTN: RZ

AIR FORCE CTR FOR STUDIES & ANALYSIS
ATTN: AFCSA/SAS
ATTN: AFSAA/SAKI

AIR FORCE ELECTRONIC WARFARE CTR
ATTN: MAJ J BIGELOW

AIR FORCE ELECTRONICS COMMAND/ET
ATTN: CAPT W WHEELER

AIR FORCE ENGINEERING & SERVICES CTR/DEMM
ATTN: CESA/ENE D CONKLING
ATTN: D A CONKLING AFCESA/ENE
ATTN: M KATONA AFCESA/RD

AIR FORCE INSPECTION & SAFETY CENTER
ATTN: AFISC/SEV
ATTN: COL D ALGIRE SES

AIR FORCE INSTITUTE OF TECHNOLOGY/EN
ATTN: LTCOL R TUTTLE

AIR FORCE MATERIAL COMMAND
ATTN: AFMC/XRNA CAPT K HUNIGAN
ATTN: YAGD MSGT R ROGAN

AIR FORCE OPERATIONAL TEST & EVAL CTR
ATTN: CNP
ATTN: DR M WILLIAMS
ATTN: LGAW
ATTN: LG4S
ATTN: MAJ ARTMAN
ATTN: MAJ MARC STRICKLAND
ATTN: OAS R DEFFENBAUGH
ATTN: OASZ
ATTN: OAW
ATTN: OAWF
ATTN: OAWV
ATTN: OAY
ATTN: OAYS
ATTN: ST
ATTN: TEFG
ATTN: TEKA
ATTN: TET
ATTN: TEWD
ATTN: TEZN MAJ TOM HERRING
ATTN: TZN

AIR FORCE SPACE COMMAMD (LKI)
ATTN: CAPT WEIDNER
ATTN: LT D BARRON
ATTN: MAJ D ROBINSON
ATTN: STOP 7

AIR FORCE SPACE COMMAND
ATTN: 2CS/CC

AIR FORCE SPACE COMMAND
ATTN: 7TH MISSILE WARNING SQ/CC

AIR FORCE SPACE COMMAND
ATTN: 4 SCS/DW

AIR FORCE SPACE TECHNOLOGY CENTER
ATTN: DR J JANNI
ATTN: SWL V OTERA

AIR TRAINING COMMAND
ATTN: TTDA

AIR WEATHER SERVICE, MAC
ATTN: AWS TECH LIBRARY

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